BULK CARBON NANOTUBE AS THERMAL SENSING AND ELECTRONIC CIRCUIT ELEMENTS

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ABSTRACT

Bulk multi-walled carbon nanotube (MWNT) were successfully and repeatably manipulated by AC electrophoresis to form resistive elements between Au microelectrodes and were demonstrated to potentially serve as novel temperature sensor and simple electronic circuit elements. We have measured the temperature coefficient of resistance (TCR) of these MWNT bundles and also integrated them into constant current configuration for dynamic characterizations. The I-V measurements of the resulting devices revealed that their power consumption were in μW range. Besides, the frequency responses of the tested devices were generally over 100 kHz in constant current mode operation. Using the same technique, bulk MWNT was manipulated between three-terminal microelectrodes to form a simple potential dividing device. The tested device was capable of dividing the input potential into 2.7:1 ratio. Our demonstrations showed that carbon nanotube is a promising material for fabricating ultra low power consumption devices for future sensing and electronic applications.

1. INTRODUCTION

Power consumption is one of the most important engineering considerations in designing electrical circuit and systems. Huge amount of efforts have been placed to minimize the power consumption of electrical systems, since high power consumption implies high heat dissipation which is undesirable in many applications. A typical example is the wall shear stress measurement in aerodynamic applications [1]. Excessive heat dissipation from a hot wire anemometrical sensor will disturb the minute fluidic motion, crippling its ability to sense true fluidic parameters. With our preliminary experimental findings on bulk MWNT, we found that bulk MWNT can be operated at μW range, which is ultra low power consumption for applications such as the shear stress and thermal sensing (e.g., in the order of mW range for typically MEMS polysilicon devices [2]). Carbon nanotubes (CNT), since discovered in 1991 by Sumio Iijima [3], have been extensively studied for their electrical [4] and mechanical properties [5]. In order to build a CNT based device, technique to manipulate the CNT has to be developed. Typical manipulation technique is by atomic force microscopy [6]. However, this conventional pick-and-place technique is time consuming, though the technique has very high positioning accuracy. Past demonstrations by K. Yamamoto et al. showed that carbon nanotube can be manipulated by AC and DC electric field [7,8]. Also, a recent report from L.A. Nagahara et al. demonstrated the individual single-walled carbon nanotube (SWNT) manipulation on nano-electrodes by AC bias voltage [9]. By using similar technique, we have successfully and efficiently manipulated bulk carbon nanotube to form resistive elements between Au microelectrodes for sensing and electronic circuits. This paper reports the technique to form bulk MWNT resistive elements between Au electrodes and our preliminary experimental findings on the electrical characterizations such as frequency response and I-V characteristics of the bulk MWNT devices. The results indicated that the carbon nanotube is promising to be used as high performance and low power consumption devices for future electronic and sensing applications.

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2. FORMATION OF CARBON NANOTUBE RESISTIVE ELEMENTS BY AC ELECTROPHORESIS

2.1 Fabrication of Microelectrodes

Array of Au microelectrodes with different geometrical shapes (see Figure 1) were fabricated on a 1.8 X 1.8 cm^2 glass substrate with standard photolithography process and wet etching process for carbon nanotube manipulation. Detailed parameters for the photolithography procedures can be found in [10].

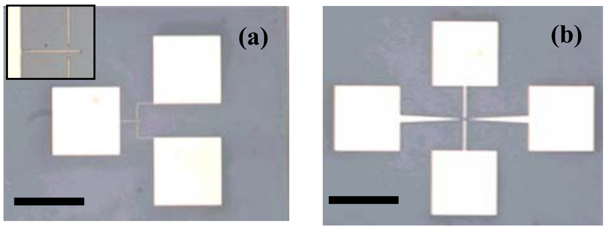

Figure 1. Optical microscopic image showing different microelectrode geometries for MWNT manipulations, a) three-terminal microelectrodes (inset showing the gap (~ 5 μm) between the microelectrodes), b) four-terminal microelectrodes. (Scale Bar = 200 μm)

2.2 Carbon Nanotube Manipulations by AC Electrophoresis

AC electrophoresis (or dielectrophoresis) is a phenomenon where neutral particles undergoing mechanical motion inside non-uniform AC electric field [11]. The technology has been widely employed to manipulate micro or nano entities such as virus and latex spheres in the past few years [12]. In this project, we employed the technique of AC electrophoresis to form bulk carbon nanotubes across microfabricated electrodes as resistive elements.

The MWNT we used in the experiments was ordered commercially from [13]. According to the specifications provided, the MWNT was prepared by chemical vapour deposition. The axial dimensions and diameters of the MWNT was 1 – 10 µm and 10 – 30 nm, respectively. Prior the MWNT manipulation, 50 mg of the sample was ultrasonically dispersed in 500 ml ethanol solution and the resulting solution was diluted to 0.01 mg/ml for later usage.

After the Au microelectrodes were wire-bonded to the external circuits, about 10 µL of the MWNT/ethanol solution was transferred to the substrate by 6 mL gas syringe. Then the Au microelectrodes were excited by AC voltage source by applying 16 V peak-to-peak at 1 MHz typically (see Figure 2). The ethanol was evaporated away (within 20 seconds to 1 minute) leaving the MWNT to reside between the gap of the microelectrodes (see Figure 3).

We experimentally discovered that the resistances of bulk MWNT resistive elements were sample dependent (i.e. different MWNT samples have different room temperature resistances) and the two probe room temperature resistances of the samples were typically ranging from several kOhm to several hundred kOhm. The reason behind for this dependency was due to the complex MWNT network formation during the process of AC electrophoresis. Since the conductivity of CNT was dependent on its lattice geometry formation during the CNT growing process, therefore, the conductivities of individual CNTs cannot be well controlled and resulting in varying conductivities in individual CNTs. As a result, it is logically followed that different bulk MWNT samples exhibited different conductivities.

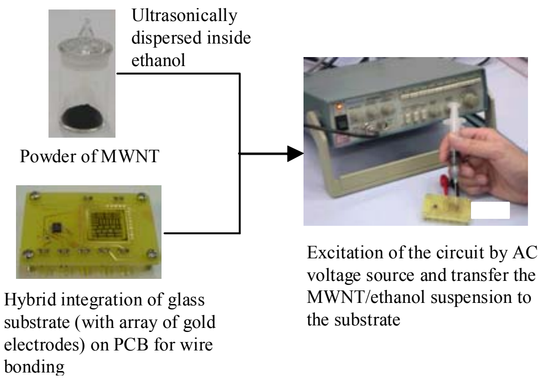

Figure 2. Experimental process flow showing the fabrication of MWNT based circuit elements.

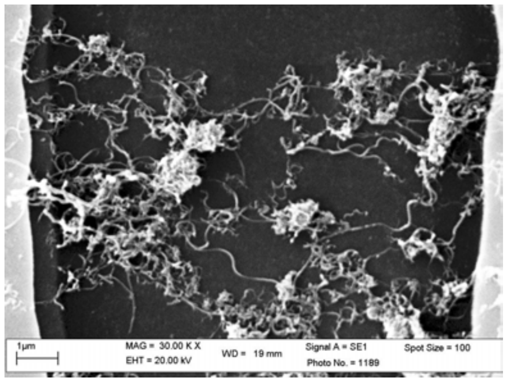

Figure 3. Scanning electron microscope (SEM) image showing the bundled MWNT connections between Au microelectrodes. (Scale Bar = 1 µm)

3. CARBON NANOTUBE AS THERMAL SENSING ELEMENT

3.1 Thermal Sensitivity

In order to measure the temperature-resistance relationship of the bulk MWNT device, the hybridly integrated circuit was put inside an oven (Lab-Line® L-C Oven) and the temperature was kept monitored by the Fluke type K thermocouple attached on the surface of the circuit board. The resistance of the bulk MWNT was then measured by Fluke 73III multi-meter. The temperature coefficient of resistance (TCR) was obtained by measuring the resistance of the bulk MWNT with the corresponding temperature. From the experimental measurements on a typical bulk MWNT device, the resistance dropped with increasing temperature, which is in agreement with [14] (i.e. negative TCR). Interestingly, the TCR measurements of all of our testing devices did not converge but the ranges were generally within -0.1 to -0.2 %/°C . Considerably drifting in room temperature resistances of the sensors were found during measurements (see Figure 4). We suspect the variations were contributed by the mismatch in thermal coefficient of expansion (TCE) between the Au electrodes and the bulk MWNT, causing some of the MWNT linkages to detach from the Au electrodes during measurements inside the oven. Another possible reason was due to contaminations to the sample such as moisture during measurements. In order to form a more robust protection to the bulk MWNT, we are currently developing a process to embed the MWNT inside parylene C diaphragms (see Figure 5). The effectiveness of the proposed method will be published elsewhere later. Nevertheless, the temperature-resistance dependency of bulk MWNT implied its thermal sensing capability. Besides, from the I-V measurement of the bulk MWNT device, the current required to induce the self heating of the device was in µA range at several volts, which suggested the power consumption of the device was in µW range (see Figure 6).

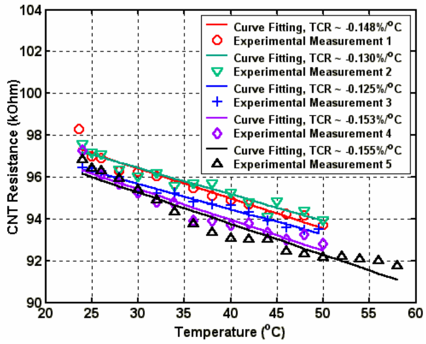

Figure 4. TCR for a typical bulk MWNT device in different measurements. Five repeated measurements were carried out for repeatability test. Considerably room temperature resistance drifting was observed in these measurements.

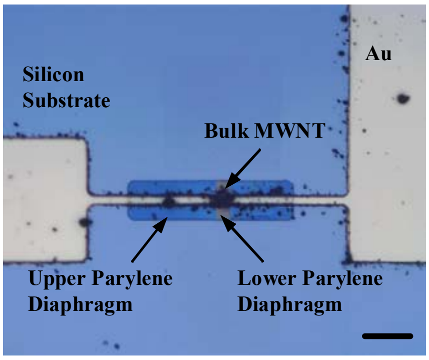

Figure 5. Optical microscopic image showing the prototyping device and the bulk MWNT was protected inside parylene C diaphragms. (Scale Bar = 20 μm)

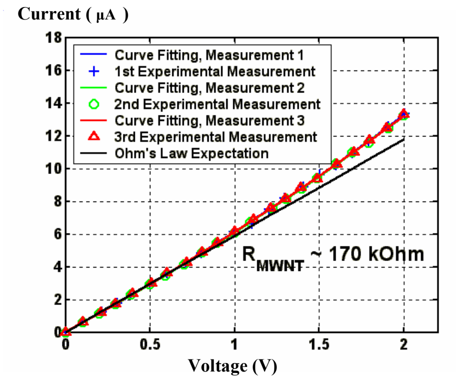

Figure 6. I-V characteristics of a typical bulk MWNT device. Three repeated measurements were performed to validate its repeatability. Non-linearity began when the applied voltage reached 0.6 V at 3.6 μA . Experimental measurements were fitted into second order curve using least square method by MatLAB® software. The straight line is the theoretical expectation using Ohm's Law and the resistance of bulk MWNT resistive elements in our sample was about 170 kΩ .

3.2 Frequency Response

In order to pick up small variations of the sensing environment, sensors with fast frequency response are highly desirable. To test the frequency response of the bulk MWNT device, input square wave of 2 V peak-to-peak at 10 kHz was fed into the hybridly integrated circuit and the output response was determined (see Figure 7). From our experimental measurements, bulk MWNT devices exhibited very fast frequency response. Using the approximation between the time constant and cutoff frequency [2],

$$f_c = 1/1.5t_c \qquad (1)$$

where f_c is the cutoff frequency, t_c is the time constant of the response, the estimated cutoff frequency of the device was about 177 kHz (see Figure 7). As a comparison, typical cutoff frequency of MEMS polysilicon sensors in constant current mode configuration without frequency compensation is around several hundred Hz to several kHz [1, 2, 15].

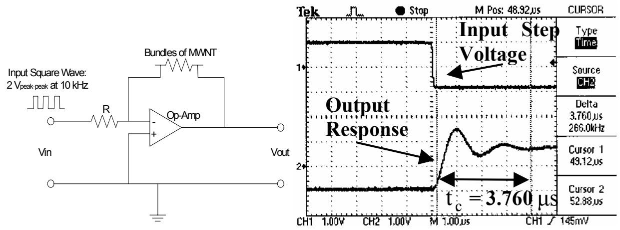

Figure 7. Output response obtained by feeding an input square wave at 2V peak-to-peak at 10 kHz into the circuit (Left). The output response was inverted due to the property of inverted amplifier configuration (Right).

4. CARBON NANOTUBE AS POTENTIAL DIVIDING DEVICE

Using the technique reported in Section 2, bulk MWNT were manipulated by a three-terminal Au microelectrodes (in Figure 1a) to form a simple potential dividing circuit (see Figure 8). Two probe resistivity measurements at room temperature for the terminals 1-2, 1-3 and 3-2 were about 1141 kΩ , 307 kΩ and 833 kΩ respectively.

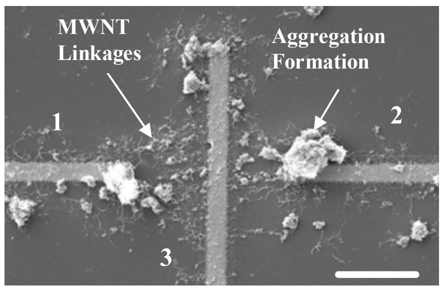

Figure 8. . SEM image showing the formation of MWNT linkages with three-terminal microelectrodes. Aggregation was observed and this was due to the instability of MWNT in ethanol medium. Terminals 1, 2 and 3 are indicated in the figure. (Scale Bar = 6 μm)

We have calculated the theoretical results based on the potential dividing formula of the resistive circuit,

$$V_{13} = \frac{R_{13}}{R_{12}} \cdot V_{12}, \quad V_{32} = \frac{R_{32}}{R_{12}} \cdot V_{12} \qquad (2)$$

where R_{12}, R_{13} and R_{32} are the resistances across the terminal 1-2 ,terminal 1-3 and terminal 3-2 respectively. V_{12} is the voltage applied across terminal 1-2. The MWNT linkages incorporated with the three-terminal microelectrodes can be used as a potential dividing circuit. The device was capable to switch the input potential into a ratio about 2.7:1(see Figure 9). The I-V measurements on terminal 1-3 and terminal 3-2 revealed the power consumption of the bulk MWNT device was in µW range (see Figure 10).

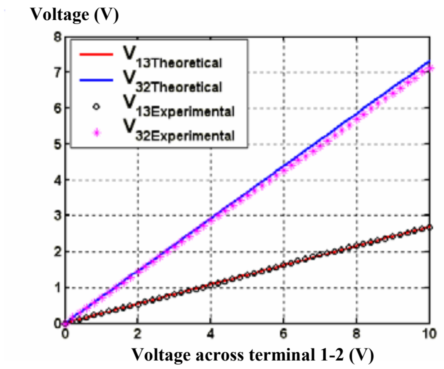

Figure 9. Comparison between the theoretical calculations and experimental results of the MWNT potential dividing circuit. The theoretical calculations are based on the potential dividing formula of a general resistive circuit.

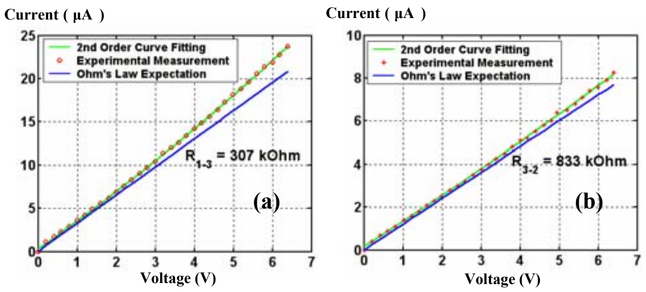

Figure 10. I-V characteristics for terminals a) 1-3 and b) 3-2. Due to the electrical conductivity dependency on different combinations of MWNT bundles, the non-linearity begun at different applied voltages in terminal 1-3 and 3-2 respectively.

5. SUMMARY

A technique to form bulk MWNT resistive elements between Au electrodes was presented. The TCR measurements and the frequency response measurement of the bulk MWNT based device showed that bulk MWNT can be used as sensing element for thermal sensing applications. Besides, the operating power of the resulting device was in µW range which is ultra low power consumption for applications such as shear stress sensing. Apart from this, a bulk MWNT based potential dividing circuit was fabricated with potential switching capability of 2.7:1 ratio and power consumption in µW range. From these demonstrations, we believe that bulk MWNT can be used for ultra low power sensing and electronic circuit applications.

6. REFERENCES

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